VARIABLE-GAIN CONSTANT-BANDWIDTH TRANSIMPEDANCE AMPLIFIER

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is related to United States Patent Application Nos. 10/072,843 filed on February 2, 2002 and 10/459,731 filed on July 11, 2003, which are hereby incorporated herein by reference.

FIELD OF THE INVENTION

[0002] The present invention relates to transimpedance amplifiers, and more particularly to a transimpedance amplifier having a relatively constant bandwidth at different gain levels.

BACKGROUND OF THE INVENTION

[0003] Operational amplifiers (opamps) are used in many different types of circuits including preamplifiers, variable gain amplifiers and the like. Referring now to FIG. 1A, an amplifier 20 includes an opamp 24 and a feedback path 28 that couples an output of the opamp 24 to an inverting input thereof. The non-inverting input is coupled to ground or another reference potential. The amplifier 20 in FIG. 1A has a gain value of one. For this reason, the amplifier 20 is usually called a unity-gain amplifier or buffer.

[0004] Referring now to FIG. 2A, an amplifier 30 is shown that is similar to the unity-gain amplifier 20 in FIG. 1A. However, in the amplifier 30, a resistance R is provided in the feedback path 28. Another resistance R is

connected between an input of the amplifier 30 and the inverting input of the opamp 24. The amplifier 30 has a gain value of two.

[0005] The most relevant characteristics of an amplifier circuit are usually gain and bandwidth. In order to derive the bandwidth, an open loop response technique is used. The technique of looking at the open loop response provides information relating to the bandwidth and maximum achievable bandwidth of an amplifier circuit.

[0006] The DC gain of the open loop response is determined by opening the feedback loop and attaching a voltage source to an input side of the opened feedback loop. The output voltage is sensed at an output side of the opened feedback loop. Open loop response versions of the circuits in FIGs. 1A and 2A are shown in FIGs. 1B and 2B. To derive the bandwidth, the DC gain of the open loop response and the first dominant pole P_1 are found. Assuming stable operation, there is only one dominant pole P_1 located below the crossover frequency. The crossover frequency is the product of the DC gain of the open loop response and the first dominant pole P_1. The crossover frequency usually defines the bandwidth of the closed-loop amplifier. The maximum available bandwidth is related to the second non-dominant pole P_2.

[0007] Referring now to FIGs. 3A and 3B, the open loop response for the amplifiers in FIGs. 1B and 2B is shown, respectively. There is a constant gain from DC to a frequency of the first dominant pole P_1. At the frequency of the pole P_1, the gain begins falling. There is an inverse relationship between gain and bandwidth of the amplifiers 20 and 30. In FIG. 3A, the amplifier 20 has a

gain of one. Therefore, the gain is constant until the zero crossing. In FIG. 3B, the gain is two until the intersection with the open loop response. In general, higher gain values are associated with lower bandwidth and lower gain values are associated with higher bandwidth. The bandwidth of the amplifier 30 is approximately half of the bandwidth of the unity-gain amplifier 20 while the gain of the amplifier 30 is twice the gain of the amplifier 20.

[0008] Referring now to FIG. 4, it may be desirable to adjust the frequency of poles P_1 and P_2 for some applications. For example, it may be desirable for the amplifier to provide a relatively constant bandwidth at different gain values. In FIG. 4, the gain values are relatively constant from DC up to the frequency of the first dominant pole P_1. Because the first dominant pole P_1 is close to the second non-dominant P_2, the gain values fall off sharply upon reaching the first dominant pole P_1.

[0009] Various compensation techniques are known for adjusting the frequency of the poles of the amplifier. The opamp may be implemented using a two-stage amplifier. In two-stage amplifiers, Miller compensation and Ahuja compensation are sometimes used. Miller compensation employs a feedback capacitor connected across an input and output of the second stage amplifier. In Ahuja compensation, a current gain device is added in the feedback loop of the second stage amplifier. Another compensation technique is used in folded cascode circuits that are output compensated. Specifically, a capacitor is coupled to an output of the circuit.

[0010] Referring now to FIGs. 3A, 3B and 5, it is difficult to adjust the frequencies of the poles P_1 and P_2 shown in FIGs. 3A and 3B without creating stability problems. In FIG. 5, the phase response that is associated with the open loop responses of FIGs. 3A and 3B is shown. The phase response is 180 degrees from DC to about the frequency of the first pole P_1. At the frequency of pole P_1, the phase response is approximately 90 degrees. The phase response remains at 90 degrees from the frequency of the first dominant pole P_1 until about the frequency of the second non-dominant pole P_2. At the frequency of the second non-dominant pole P_2, the phase response is approximately zero degrees.

[0011] The phase response in FIG. 5 also illustrates a phase margin of approximately 90 degrees. The phase margin is usually defined at unity gain. For acceptable stability, the phase margin should be greater than approximately 55-60 degrees otherwise oscillation will occur. Therefore, the 90 degree phase margin that is shown in FIG. 5 is typically acceptable. However, moving the frequency of the second non-dominant pole P_2 closer to the zero crossing will reduce the phase margin. At some point, this will cause oscillation. Conversely, moving the first dominant pole P_1 closer to the zero crossing in FIGs. 3A and 3B will increase the phase margin. At some point, this too will cause oscillation. For these reasons, it is generally not possible to adjust the frequencies of the poles P_1 and P_2 shown in FIGs. 3A and 3B to produce the open loop response of FIG. 4 without creating stability problems.

[0012] Referring now to FIGs. 6A and 6B, a transimpedance amplifier (TIA) 60 includes an opamp 64 having a transconductance value ($-g_m$). The opamp 64 has a feedback resistor (R_f) 66. A capacitance (C_1) 70 is connected between an input of the TIA 60 and ground or a reference potential. Another capacitance (C_2) 72 and a load resistance (R_L) 74 are connected between the output of the TIA 60 and ground or a reference potential. An input 76 to the TIA 60 is a current I and an output 80 of the TIA 60 is a voltage V.

[0013] Referring now to FIG. 7, the open loop response for the TIA 60 in FIG. 6B is shown. At DC, the gain is equal to $g_m R_L$. If we assume that the capacitance C_1 is much greater than the capacitance C_2 and the resistance R_f is large, the frequency of the first dominant pole $P_1 = 1/(C_1 R_f)$. Further, the frequency of the second non-dominant pole $P_2 = 1/(C_2 * (R_L$ in parallel with $R_f))$. The zero crossing occurs at a frequency of $(g_m R_L)/(C_1 R_f)$.

[0014] Referring now to FIG. 8, the closed loop response for the TIA 60 is shown. Two different gain curves are illustrated in FIG. 8. One curve corresponds to the resistance $R_f = R_{f1}$ and the other curve corresponds to the resistance $R_f = R_{f2}$, where $R_{f2} > R_{f1}$. For a given value of R_f, higher gain is associated with lower bandwidth and lower gain is associated with higher bandwidth.

SUMMARY OF THE INVENTION

[0015] A transimpedance amplifier (TIA) circuit according to the present invention includes a first opamp having an input and an output. A

second opamp has an input that communicates with the first opamp and an output. A first feedback path communicates with the input and the output of the first opamp and includes a first resistance. A second feedback path communicates with the input and the output of the second opamp and includes a second resistance. A third feedback path communicates with the input of the first opamp and the output of the second opamp.

[0016] In other features, the first feedback path includes a first capacitance in parallel with the first resistance. The second feedback path includes a second capacitance in parallel with the second resistance. The first feedback path further includes a third resistance in series with the first resistance and the first capacitance. The third resistance has a resistance value that is approximately two times a resistance value of the first resistance. The first and third resistances have substantially equal resistance values. The second feedback path further includes a fourth resistance in series with the second resistance and the second capacitance. The fourth resistance has a resistance value that is approximately two times a resistance value of the second resistance. The second and fourth resistances have substantially equal resistance values. The first and second capacitances have substantially equal capacitance values.

[0017] In other features, a third opamp has an input that communicates with the output of the first opamp and an output that communicates with the input of the second opamp. The third feedback path includes a fifth resistance. Third, fourth and fifth capacitances have one end that communicates with the inputs of

the first, second and third opamps, respectively. A sixth capacitance communicates with the output of the second opamp.

[0018] In other features, a preamplifier comprises the TIA circuit. A hard disk drive comprises the preamplifier. A variable gain amplifier comprises the TIA circuit. A read channel circuit comprises the variable gain amplifier.

[0019] Further areas of applicability of the present invention will become apparent from the detailed description provided hereinafter. It should be understood that the detailed description and specific examples, while indicating the preferred embodiment of the invention, are intended for purposes of illustration only and are not intended to limit the scope of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0020] The present invention will become more fully understood from the detailed description and the accompanying drawings, wherein:

[0021] FIGs. 1A and 2A are electrical schematics of amplifier circuits according to the prior art;

[0022] FIGs. 1B and 2B are electrical schematics of the circuits of FIGs. 1A and 2A in an open loop response configuration;

[0023] FIGs. 3A and 3B are graphs illustrating the open loop responses of the amplifiers of FIGs. 1B and 2B;

[0024] FIG. 4 is a graph illustrating a desired closed loop gain response for the amplifiers of FIGs. 1A and 2A;

[0025] FIG. 5 is a graph illustrating the phase response corresponding to the open loop response of FIGs. 3A and 3B;

[0026] FIGs. 6A and 6B are electrical schematics of TIA circuits according to the prior art in closed loop and open-loop response configurations;

[0027] FIG. 7 is a graph illustrating the open loop gain response for the TIA of FIG. 6B;

[0028] FIG. 8 is a graph illustrating the open loop gain response of the TIA of FIG. 6 for two different values of a resistance R_f;

[0029] FIG. 9 is an electrical schematic of a multi-stage TIA according to the present invention;

[0030] FIG. 10 is a graph illustrating the open loop response for the TIA of FIG. 9;

[0031] FIG. 11 is a graph illustrating the gain of the TIA of FIG. 9 as a function of a resistance $R_{f;}$

[0032] FIGs. 12A and 12B are electrical schematics of a variable-gain constant-bandwidth TIA according to the present invention;

[0033] FIG. 13 is a graph of the gain of the TIA of FIG. 12 as a function of a resistance R_f;

[0034] FIG. 14 is a graph of the closed loop gain of the TIA of FIG. 12;

[0035] FIGs. 15A and 15B illustrate the gain of the TIA of FIG. 12 at low frequency and high frequency, respectively;

[0036] FIG. 16 illustrates the TIA of FIG. 12 in a preamplifier of a hard disk drive system; and

[0037] FIG. 17 illustrates the TIA of FIG. 12 in a variable gain amplifier of a read channel circuit.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0038] The following description of the preferred embodiment(s) is merely exemplary in nature and is in no way intended to limit the invention, its application, or uses. For purposes of clarity, the same reference numbers will be used in the drawings to identify similar elements.

[0039] Referring now to FIG. 9, a multi-stage TIA 90 converts an input current I at 92 into an output voltage V at 94. The TIA 90 includes a first opamp 96, a second opamp 98 and a third opamp 100 that are coupled in series between the input and the output of the TIA 90. The opamps 96, 98 and 100 have transconductance values $-g_{m1}$, $-g_{m2}$ and $-g_{m3}$, respectively. A resistance (R_1) 104 is connected between the input and the output of the first opamp 96. Another resistance (R_3) 106 is connected between the input and the output of the third opamp 100. A resistance (R_f) 108 is connected between the input and the output of the TIA 90. Capacitors and/or capacitances C_1, C_2, and C_3 (109, 110, and 112, respectively) are coupled between the inputs of opamps 96, 98, and 100, respectively, and ground (or another reference potential). Additionally, a capacitor and/or capacitance (C_4) 960 is coupled between the output of the TIA 90 and ground (or another reference potential).

[0040] Referring now to FIG. 10, the open loop response of the TIA 90 is shown. The resistance $R_f >> 1/g_{m1}$ and the gain produced by the first opamp

96 is R_1/R_f. Additionally, $g_{m1}/C_1 \approx g_{m1}/C_2 \approx g_{m3}/C_3 \approx g_{m3}/C_4$ such that the poles produced by the capacitors C_1-C_4 are closely spaced. There is no dominant pole. The DC gain is equal to $(R_1/R_f)g_{m2}R_3$. This gain value remains relatively constant until the closely spaced pole frequencies. At those frequencies, the gain falls off sharply, as shown in FIG. 10. FIG. 10 illustrates a nearly constant bandwidth for a range of gain values. However, given the above assumptions regarding the gain parameters and capacitor values, the TIA 90 may experience phase margin problems when operating above unity gain.

[0041] Referring now to FIG. 11, it is possible to operate the TIA 90 below unity gain using high values of the resistance R_f. However, limited gain variation can be realized. This is illustrated in Fig. 11, where the gain is shown as a function of the resistance R_f. When the value of resistance R_f is infinite, the gain is equal to $R_1g_{m2}R_3$. When $R_f = R_1g_{m2}R_3$, the gain is unity. When it is above this value, the gain cannot be varied much and the circuit is stable. When $R_f < R_1g_{m2}R_3$, the gain can be varied but the circuit is unstable.

[0042] Referring now to FIGs. 12A, 12B, 15A and 15B, a TIA 150 according to one embodiment of the present invention is shown. The TIA 150 includes a feedback path 154 that communicates with the input and the output of the opamp 96. In FIG. 12A, the feedback path 154 has a resistance that decreases as frequency increases. For example and referring now to FIG. 12B, the feedback path 154 can include a resistor R_{1a} 158 connected in series with the parallel combination of a resistor R_{1b} 162 and a capacitor and/or capacitance (C_{P1}) 166. At low frequencies, the capacitor 166 is essentially an open circuit

and the resistance of the feedback path 154 is essentially $R_1 = R_{1a}+R_{1b}$. At high frequencies, the capacitor 166 shunts the resistor 162 and the resistance of the feedback path 154 is essentially R_{1a}. The combination of resistances R_{1a} and R_{1b} and the capacitance C_{P1} provide a variable resistance that decreases with increases in frequency.

[0043] The TIA 150 further includes a feedback path 170 that communicates with the input and the output of the opamp 100. In FIG. 12A, the feedback path 170 has a resistance that decreases with increases in frequency. For example and referring now to FIG. 12B, the feedback path 170 includes a resistor R_{3a} 172 connected in series with the parallel combination of a resistor R_{3b} 173 and a capacitor and/or capacitance (C_{P3}) 174. While a combination of resistances and capacitances are shown, any other suitable techniques for providing a variable resistance may be used. For example, transistors can be used to short resistances and conventional approaches may be used. At low frequencies, the capacitor 174 is essentially an open circuit and the resistance of the feedback path 170 is essentially $R_3 = R_{3a}+R_{3b}$. At high frequencies, the capacitor 174 shunts the resistor 173 and the resistance of the feedback path 170 is essentially R_{3a}. The effect of this resistive transition is shown in FIGs. 15A and 15B. Likewise, the combination of resistances R_{3a} and R_{3b} and the capacitance C_{P3} provide a variable resistance that decreases with increasing frequency.

[0044] Referring now to FIG. 13, the gain response for the TIA 150 is shown as a function of the resistance R_f. A maximum gain equal to $R_1 g_{m2} R_3$ can

be produced at DC. A minimum gain equal to $R_1g_{m2}R_3/9$ can be produced at frequencies greater than $3/C_{P1}R_1$ and $3/C_{P3}R_3$ when $R_{3a} = 2R_{3b}$ and $R_{1a} = 2R_{1b}$. Between these maximum and minimum gain levels, a linear gain variation region exists. Within the linear gain variation region, a desired above-unity gain level can be obtained by choosing an appropriate value of the resistance R_f.

[0045] Referring now to FIG. 14, the gain of the TIA 150 is shown for different values of resistance R_{f1}, R_{f2}, R_{f3}, and R_{f4}. Assuming $g_{m1}/C_1 \approx g_{m1}/C_2 \approx g_{m3}/C_3 \approx g_{m3}/C_4$, the non-dominant poles produced by capacitors C_1-C_4 are closely spaced. Therefore, each gain curve is relatively constant until reaching the closely spaced pole frequencies. At those higher frequencies, the gain falls off sharply. Thus, varying the gain of the TIA 150 (by varying the resistance R_f) produces only minimal variation in bandwidth.

[0046] Further, by choosing suitable transconductance and capacitance values, the poles of the TIA 150 are closely spaced at high frequencies. Therefore, the TIA 150 has a relatively constant bandwidth up to the non-dominant pole frequencies. At those frequencies, the gain drops off rapidly.

[0047] It should be understood that various values can be selected for the transconductance values g_{m1}, g_{m2}, and g_{m3}. For example, the same transconductance value can be used for all of the opamps 96, 98 and 100. Alternatively, each transconductance value can be different than one or more other transconductance values. For example, a larger value of g_{m1} can be used for input noise or input impedance purposes. Further, a larger value of g_{m3} can

be used for output impedance purposes. However, it should be understood that other transconductance values can be used without departing from the scope of the invention.

[0048] Similarly, resistances R_{1a}, R_{1b}, R_{3a}, and R_{3b}, as well as capacitances C_1, C_2, C_3, C_4, C_{P1} and C_{P3}, can be selected as desired for any given application of the invention. For example, resistors 158 and 172 can be twice as large as resistors 162 and 173, respectively, and the values of capacitors C_{P1} and C_{P3} can be the same. However, other resistance and capacitance values can be used without departing from the teachings of the present invention. For some preferred embodiments, the value of resistors 158, 162, 172, and 173 are the same. In some embodiments, the transistors in the op-amps are CMOS transistors.

[0049] Referring now to FIGs. 16 and 17, various exemplary applications are shown. In FIG. 16, the TIA 150 according to the present invention is employed by a preamplifier 200 of a hard disk drive system 210. In FIG. 17, the TIA 150 is implemented in a variable gain amplifier (VGA) 220 of a read channel circuit. Skilled artisans will appreciate that the TIA is suitable for other applications requiring a relatively constant bandwidth at various above-unity gain levels.

[0050] As can be appreciated, the TIA circuit according to the present invention provides constant bandwidth over a wide range of gain values. For example, one implementation provides a gain range of 5-50 or greater. Those skilled in the art can now appreciate from the foregoing description that the broad

teachings of the present invention can be implemented in a variety of forms. Therefore, while this invention has been described in connection with particular examples thereof, the true scope of the invention should not be so limited since other modifications will become apparent to the skilled practitioner upon a study of the drawings, the specification and the following claims.